



Linking resource supplies and price drivers: Lessons from Traditional Chinese Medicine (TCM) price volatility and change, 2002–2017

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ABSTRACT

Ethnopharmacological relevance: Worldwide, one of the drivers of substitution and adulteration is the cost of the natural resources (plants, animals, fungi) that are ingredients of traditional medicines. Relatively few studies have been done that link prices of traditional medicine ingredients to what drives changes in price, yet this is an important topic. Theoretically, prices have been widely considered as an economic indicator of resource scarcity. Rare, slow growing medicinal plants sell for high prices and common, less popular species for low prices. Price levels also influence the viability of farming vs. wild harvest (and incentives to overharvest high value species when tenure is weak). Prices can also influence the harvesting or buying behaviour of harvesters, traders or manufacturers. When prices are high, then there is a greater incentive to use cheaper substitute species or adulterants. As previous studies on herbal medicine ingredients have shown, adulteration applies in a wide variety of cases, including to some Traditional Chinese Medicine (TCM) species.

Aim of the study: The aim of this study was to gain a better understanding of which factors influenced changes in the market prices of document prices for four popular, but very different traditional Chinese medicine (TCM) species (2002–2017).

Materials and methods: Fluctuations in market prices were followed over a 15-year period (2002–2017) for four very different TCM ingredients: two plant species (one wild harvested for fruits (*Schisandra sphenanthera* Rehder & E.H. Wilson) the other in a transition from wild harvest to cultivation (*Paris polyphylla* Smith), an animal species (the Tokay gecko (*Gekko gekko* L.)) and the entomophagous “caterpillar fungus” (*Ophiocordyceps sinensis* (Berk). G.H. Sung, J.M. Sung, Hywel-Jones & Spatafora).

Results: High prices of medicinal plants are widely considered to reflect resource scarcity. Real-time market prices for three of the four very different TCM species we studied all showed major price fluctuations. The exception was *P. polyphylla*, whose wild populations are widely known to be increasingly scarce, where there was a steady increase in price, with few fluctuations in the upward price trend. The three other species showed significant price fluctuations. These were driven by multiple factors. Ecological and biogeographic factors that influence abundance or scarcity of supply certainly played a role. But other factors were also influential. These included both national and global economic factors (the influence of the Global Financial Crisis (GFC)), national policy changes that in turn influenced businessmen giving expensive gifts (that included *O. sinensis*), climate change (influencing fruiting success of *S. sphenanthera*), price speculation by traders and lack of information (e.g. reduction in *G. gekko* prices due to traders incorrectly believing that domestication would increase supplies).

Conclusions: Price fluctuations in the four TCM species we examined are influenced by many factors and not just resource scarcity. And the situation is more complex than the trajectory based on Homma's (1992) model, where he predicted that higher prices would result in a shift to cultivation, thus replacing wild harvest. In case of both *O. sinensis* and *P. polyphylla*, Homma (1992, 1996) was right in terms of scarcity and high prices stimulating a major investment in cultivation (*P. polyphylla*) and artificial production (*O. sinensis*). But in both cases, intensive production through cultivation or artificial propagation do not yet occur on a large enough scale to reduce harvest of wild stocks. Substitution and adulteration occur with all four species. Improving information to

Abbreviations: asl, above sea level; CNY, Chinese Yuan Renminbi; GFC, Global Financial Crisis; NTFP's, non-timber forest products; SARS, Severe Acute Respiratory Syndrome; TCM, traditional Chinese medicine; UK, United Kingdom; USA, United States of America

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medicinal plant traders on the supply status of TCM stocks, whether from wild harvest or from cultivation could benefit product quality, cultivation initiatives and conservation efforts.

1. Introduction

At a global scale, across diverse traditional medical systems, concern is widely expressed about adulteration and substitution, particularly when these reduce efficacy of herbal medicines or cause adverse effects (Foster, 2011; Parveen et al., 2016). Price increases provide an incentive to unscrupulous suppliers to adulterate with cheaper or more common species. Despite the links between prices, efficacy and traditional medicine supplies, few studies have been done on what influences medicinal product prices. High prices can also drive over-exploitation and unsustainable use. While scarcity of supplies of popular, wild harvested traditional medicines can drive up prices, there are few long-term studies of the different factors that influence traditional medicine prices. Yet studies of price trends are relevant to a better understanding of sustainable wild harvest, cultivation and product quality.

The economic theory that prices are an economic indicator of resource scarcity has been criticised by economists such as Norgaard (1990) and Neumayer (2000) in the case of a broad category of natural resources, although not applied to traditional medicines. More generally, for non-timber forest products (NTFP's), several researchers have developed hypotheses that link commercial market demand to the selective harvesting of economically valuable forest products (Homma, 1992, 1996; Godoy and Bawa, 1993; Wilkie and Godoy, 1996). Homma (1992, 1996), for example hypothesized that as commercial demand for a forest product grew, more and more of the forest product would be harvested. Then, as quantities and quality from wild plant populations declined, prices would increase. With reduced supplies, Homma (1992) suggested that higher prices consequently resulted in a shift to cultivation of forest products to replace wild harvest. Prices paid for medicinal plants also are an important factor that influences whether cultivation is economically viable or not (Schippmann et al., 2003). Development of new products can also influence prices and a shift to alternative supply sources. Development of TAMIFLU™ (oseltamivir phosphate), in which shikimic acid (sourced from Chinese star anise (*Illicium verum* Hook f.)) is a major ingredient (Wang et al., 2011) stimulated research into microbiological methods of producing shikimic acid (Bochkov et al., 2012) and also drove up prices of this medicinal spice. Creative marketing and expansion into international markets (Potterat, 2010) have certainly stimulated cultivation of wolf-berry species (*Lycium barbarum* L. and *Lycium chinense* Mill.).

This study was carried out in China, which in terms of both economic value and volume of medicinal plants traded, is widely acknowledged to be the world's biggest exporter and importer of medicinal plants (Schippmann et al., 2003). The aim of this study was to gain a better understanding of which factors influenced changes in the market prices of document prices for four popular, but very different traditional Chinese medicine (TCM) species over a 15-year period (2002 – 2017). The four species we chose were the caterpillar fungus (*Ophiocordyceps sinensis* (Berk). G.H. Sung, J.M. Sung, Hywel-Jones & Spatafora (冬虫夏草 *Dōng Chóng Xià Cǎo*) ("winter worm-summer grass"), the Tokay gecko (*Gekko gecko* L.) and two medicinal plant species, a rhizome source (*Paris polyphylla* Smith (chong lou) and a fruit source (*Schisandra sphenanthera* Rehder & E.H. Wilson (nanwuweizi)). Each of these species, from geckos to caterpillar fungi, is traded at a significant scale.

Worldwide, at least 14 gecko species are used in traditional medicine (Bauer, 2009). Tokay geckos are the most commonly traded, both for live for the pet trade as well as being caught, disembowelled and kiln dried for use in traditional medicine (Nijman and Shepherd, 2015).

Over a decade ago, Laoong and Sribundit (2006) recorded that between 2 and 5 million Tokay geckos were exported to China, Taiwan, Malaysia, and USA annually. Live Tokay geckos are also exported to the UK (Tapley et al., 2011). In 2006, just three traders in Java, Indonesia exported about 1.2 million wild-caught geckos for use in traditional Asian medicine (Nijman et al., 2012a). More recently, the Indonesian Ministry of Forestry granted permission for six companies to export a total of over 3 million supposedly live captive-bred Tokay Geckos (Partono, 2014, cited in Nijman and Shepherd, 2015). Tokay geckos are caught in Guangxi and Jiangsu provinces of China, as well as imported from Cambodia, Indonesia, Malaysia Thailand and Vietnam (Zhao, 2004). China is the major importer of *G. gecko* where they are sold whole (Fig. 2b) or in added as an ingredient to capsules (such as Gejie Dingchuan capsules). These capsules are used to treat coughs and asthma (Zou et al., 2003; Ziment and Tashkin, 2000). According to Zou et al. (2003), Gejie Dingchuan capsules were effective in treating asthma and coughs and also had an anti-inflammatory effect without side effects.

Many studies have been done on the trade and uses of *O. sinensis*, including an excellent review by Winkler (2008), the studies by Zhu et al. (1998a, 1998b) and two papers in this special issue (He, 2018; Pouliot et al., 2018), but long-term price data for different grades of *O. sinensis* can be difficult to obtain. According to Winkler (2002), citing on-going research by Yonten Gyatso, 15th century Tibetan medical texts recorded use of *O. sinensis*, about 300 years before the first records in Chinese medical texts. Prices for *O. sinensis* have been high for centuries. For example, in one of the earliest western accounts of the *O. sinensis* trade, by Du Halde (in 1736), *O. sinensis* was worth four times its weight in silver (Pegler et al., 1994). Unlike many non-timber products, *O. sinensis* can account for a high proportion of household cash income to collectors and traders in remote parts of the Himalaya. Winkler (2008), for example records that income from sale of *O. sinensis* frequently represents 70–90% of household income.

With regard to the two focal plant species, commercial demand for *S. sphenanthera* fruits is not only for traditional medicine, but also for a "Schisandra wine". An example of export trade in *S. sphenanthera* is given in this special issue (Brinckmann et al., 2018) and the properties and uses of this species are summarized in Cunningham and Brinckmann (2010). Panossian and Wikman's (2008) review of research on *Sphenanthera chinensis* (Turcz.) Baill. is also relevant to *S. sphenanthera*. The *P. polyphylla* trade is reviewed elsewhere in this special issue (Cunningham et al., in press) and its uses were reviewed by Shah et al. (2012), so are only dealt with briefly here. *P. polyphylla* is best known for the steroidal compounds that speed up blood coagulation and as an important ingredient in Yunnan Baiyao (literally "Yunnan White Powder") that was invented in 1902 and been a feature of first-aid kits in China for decades. Between 800 and 1050 t of *P. polyphylla* rhizomes are sold annually (Cunningham et al., 2018, this issue). One indicator of future demand for products containing *P. polyphylla* is the growth of the company most closely linked to Yunnan Baiyao medicinal powder. Since 1995, the Yunnan Baiyao Group has grown rapidly as an international business, doubling its revenue to USD3.4 billion in 2016, with rising profit margins and growing market capitalization (to over US\$13 billion) (Schuman, 2017).

This paper is divided into two components. Firstly, we present the results of tracking price changes and secondly, discuss the relevant links between prices, product quality, cultivation initiatives and conservation efforts before concluding.

2. Methods and approach

Real-time monitoring of prices at major traditional medicine markets across China for TCM species by Chengdu Tiandi Net Information Technology Ltd (www.tiandi.com) enabled the compilation of long-term price data for the four focal species in this study. Major fluctuations in market prices assessed for the 15-year period (2002–2017) for four very different TCM ingredients: two plant species (one wild harvested for fruits (*Schisandra sphenanthera* Rehder & E.H. Wilson) the other in a transition from wild harvest to cultivation (*Paris polyphylla* Smith), an animal species (the Tokay gecko (*Gekko gekko* L.) and the entomophagous “caterpillar fungus” (*Ophiocordyceps sinensis* (Berk). G.H. Sung, J.M. Sung, Hywel-Jones & Spatafor). All of these species are in commercial trade, but the main reason why they were chosen is that they represented a spectrum of life-forms, a variations in geographic range and habitat specificity (from wide geographic range in the case of *G. gekko* to habitat specific (*O. sinensis*) and price ranges (from US\$8.06 CNY/kg for *G. gekko* for to US\$18726 to US\$30250 CNY/kg for *O. sinensis* in 2016). In an influential analysis of commonness or rarity, Rabinowitz et al. (1986) developed an approach to characterize the geographic distribution, habitat specificity and relative population sizes of plant species. The first choice is whether the species has a wide or narrow geographic distribution. The second choice, within that distribution, is whether the species has a wide or narrow habitat specificity. We used this to contrast the relative “supply status” of four focal species in this study (Table 1), also noting additional factors that influenced supplies of each species during the study period.

3. Results

3.1. *Gekko gekko* L. (Tokay gecko, Ge Jie (蛤蚧))

In China, Tokay geckos are graded according to size, with different prices for small, medium or large individuals. Price fluctuations, driven by a range of factors, are common, with the volatility in price are reflected across all size grades (Fig. 1).

3.2. *Ophiocordyceps sinensis* (caterpillar fungus, đông chóng xà cỏ)

The major TCM market tracks prices for five grades of *O. sinensis*, three of which are shown here, from the lowest (broken material) to the highest quality (and highest price) (Fig. 4).

3.3. *Paris polyphylla*

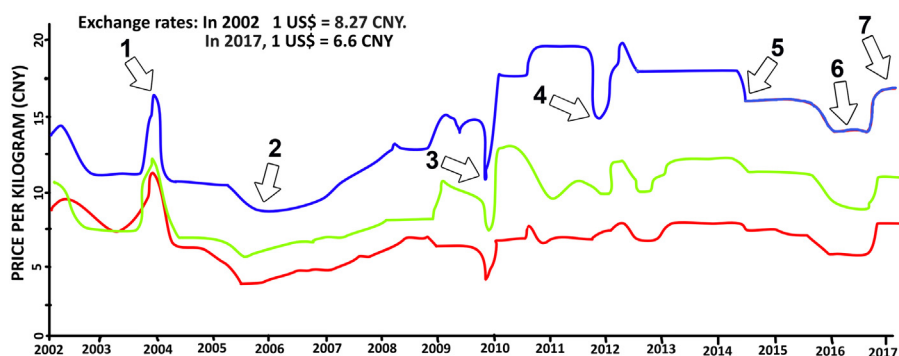
The steadily rising price for *P. polyphylla* rhizomes (Fig. 5) contrasts with the declining size of the wild harvested rhizomes in trade, despite significant investments in cultivation (Fig. 6c). Despite a significant investment in cultivation of *P. polyphylla*, reflected in a lucrative market for the seeds (Fig. 6a), there is no sign yet of a drop in the price of *P. polyphylla* rhizomes (Fig. 5).

3.4. *Schisandra sphenanthera* (南五味子)

S. sphenanthera (nan wu wei zi (meaning “southern five flavoured fruit”) is sold at a lower price than *S. chinensis* (北五味子 or bei wu wei zi, the “northern five flavoured fruit”). The main driver for the increasing *S. sphenanthera* price since 2006 (Fig. 7) is that *S. chinensis* prices have been increasing rapidly, despite the fact that *S. chinensis* is cultivated. However, within the overall trend of an increasing price are significant fluctuations. These have diverse causes, including changeable weather influencing fruit production (Fig. 8). From field experience, we know for example that unseasonal cold weather during the flowering season causes flowers to drop off and results in low *S. sphenanthera* fruit yields and reduced fruit harvests that in turn affect the market price.

Table 1
Comparison of economic values (2016) and supply factors for the four focal species in this study. Note that 1 US\$ = 6.942 CNY in 2016./.

Species	2016 Price CNY/kg (US\$/kg)	Supply factors	Geographic distribution, habitat specificity & population size	Resilience to commercial harvest	Other factors influencing supply
<i>Ophiocordyceps sinensis</i> (冬虫夏草)	130,000 – 210,000 (US\$18726 to US\$30250)	5 years	Small supply: Constantly sparse in several habitats over a small geographic area (high altitude Himalaya > 3000 m asl). Small supply: Constantly sparse in several habitats over a large geographic area	Medium-High. Each <i>O. sinensis</i> fruiting body produces large quantities of spores. Not all infected caterpillars are found. Low. Wild harvest of rhizomes removes the entire plant, sometimes before they have reproduced. Medium. Small clutch size (2 eggs, with females producing 4 clutches/yr) (Nijman and Shepherd, 2015).	Climate change: higher temperatures and moisture levels reduce spore viability. Very high altitude, so buffered from land-use change. As an underground rhizome, buffered from climate factors. Land-use change may be a factor. successful, large-scale cultivation can take pressure off wild stocks. Captive breeding is possible, but requires a huge investment that at current prices is unlikely to match export levels of millions of <i>G. gekko</i> per year (Nijman and Shepherd, 2015). Granting export quotas allowing unsustainable quantities of wild caught gecko exports pose a problem. Unseasonally cold weather during flowering or early fruiting seasons results in fruit fall and low fruit production. Habitat cleared for farming. Rules against stem cutting need to be followed.
<i>Paris polyphylla</i> (重楼)	310 (US\$44.65)	5–25 years	Large supply: Locally abundant in several habitats over a large geographic area (South & SE Asia).		
<i>Gekko gekko</i> (蛤蚧)	56 (US\$8.06)	1–1.5 years			
<i>Schisandra sphenanthera</i> (南五味子)	21 (US\$3.02)	Annual fruit production.	Medium supply: Endemic to China, but locally abundant in several habitats over a large geographic area within China.		



prices of Tokay geckos declined due to overall price declines across the TCM market; 6. The same reason for a decline occurred in late 2015 and into 2016 due to an overall decline in the TCM market. 7. Prices of Tokay geckos increased due to lower supplies and higher market demand in 2017.

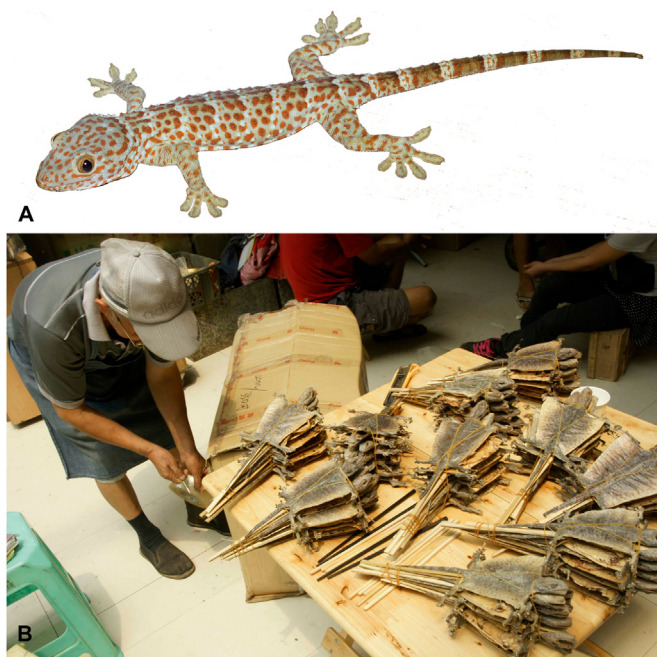


Fig. 2. A. A Tokay gecko (*Gekko gekko*). B. Kiln dried Tokay geckos, graded for size and exported from Indonesia, being unpacked at Hehuachi market, Sichuan, China: a fraction of the millions of these large geckos exported to China annually from Indonesia, Thailand and Vietnam. photos: A. B. Cunningham.

4. Discussion

The drivers of TCM ingredient prices and their volatility are often more complex than merely being price increases in response to declining stocks of the species used as raw materials. In terms of declining supplies driving up demand, *P. polyphylla* shows the closest fit to this trend, with relatively low price volatility (Fig. 5). But drivers and price volatility also vary across species. The views of the economists Norgaard (1990, 1991) and Neumayer (2000) are supported by our study, which showed that with the possible exception of *P. polyphylla*, price fluctuations in the TCM case are also influenced by many factors and not just scarcity. Many TCM traders are risk-averse and collectively, their buying behaviour is an important driver of price declines. In some cases, for example with *O. sinensis*, specialist traders of this caterpillar fungus also speculate, driving prices higher (Fig. 4, price increase 1 (in 2007/8). Improving information to medicinal plant traders on the supply status of TCM stocks, whether from wild harvest or from cultivation could benefit product quality, cultivation initiatives and conservation efforts.

Fig. 1. Tokay gecko prices 2002–2017 giving reasons for volatility: 1. Price increased in a short period due to increased capital flow in the Tokay gecko market in that year; 2. Price of Tokay geckos declined due to some TCM traders having the incorrect information that Tokay geckos had been successfully domesticated, with the expectation of large quantities of farmed geckoes entering the market. This did not occur. But nevertheless, many "risk-averse" TCM traders took a "wait-and-see" attitude on buying Tokay geckos and the price declined. 3. The price of Tokay geckos declined because the price rose too high in previous year and TCM traders held off from buying until the price fell; 4. The same happened in 2012, where the price dropped rapidly after a price increase in 2011; 5. The

Norgaard (1990), in considering the interplay between resource stocks, scarcity and prices for those resources, has criticised of the common (Ricardian model) approach that is based on the logic that "if resources and scarce and resource allocators are informed of this scarcity, then economic indicators will reflect this scarcity". In their study of the traditional medicines trade in South Africa, Williams et al. (2007) show links between supply, demand and the market values of medicinal plants and the risk of overharvest were more complex than earlier studies (such as Cunningham, 1991) suggested. With traditional medicinal plant prices in South Africa, Williams et al. (2007) found that resource scarcity was just one of several factors that influenced a species' overall value. We agree with Williams et al.'s (2007) conclusion, based on our study of 15-years of price fluctuations in the four focal TCM species. In addition to rising prices with increasing scarcity, price/kg was influenced by two categories of factors. Firstly, factors that influence prices due to their influence on demand and secondly, factors that influence supplies. From our study, it is clear that declines in sources medicinal plants, fungi or animals goes beyond fundamental influences on supply (geographic distribution, habitat specificity, population size and growth rates). Substitution and adulteration occur, but in different ways across the four species. Each of these categories of factors that influenced the price of the four focal species is discussed in detail in the sections below, noting that not all of these factors are independent of each other.

4.1. Substitution and adulteration: different drivers and differences in acceptability

Foster's (2011) practical definitions of an "adulterated product" as one where "the customer does not receive what he or she is led to believe to be purchasing" is very relevant in this study, as is his perspective on substitution. Substitution can be legitimate, when, as Foster (2011) points out, "Substitution may involve offering one substance in place of another more expensive ingredient, or substituting one substance for another that might not be readily available or available only at a much higher price. If knowingly offered by both seller and buyer as a "substitute" for another substance, then the practice may be socially (and economically) acceptable, depending upon the cultural context". There may also be cases where adulteration is unintentional or accidental, due to poor quality control measures in the supply chain. Nevertheless, improved supply chain management is important for many reasons. Substitution of *I. verum*, with toxic *Illicium* species (*Illicium anisatum* L. and *Illicium lanceolatum* A.C. Smith) can be resolved through better knowledge of the fruit characteristics of these three species (Wang et al., 2011).

In this study, with *S. spheganthera*, one of the reasons why the price for this lower cost, smaller fruited species has been driven higher is due to the rising cost of the closely related species, *S. chinensis*. So it is possible that some substitution may be occurring due to the lower price of *S. spheganthera*. The Pharmacopoeia of the People's Republic of China



Fig. 3. A. Wild harvesting of *O. sinensis*, NW Yunnan, China. B. New technology to add value: compressed air to clean carefully graded *O. sinensis*. C. Packaged *O. sinensis*. D. Cleaned, graded and "flower" displays of *O. sinensis*. E. One of the end uses: *O. sinensis* in a therapeutic soup with black-skinned chicken, which is also an important ingredient. photos: A.B. Cunningham.

(State Pharmacopoeia Commission of the PRC, 2005) gives the "indications for use" for both *S. sphenanthera* and *S. chinensis*, and at the same dosage level. Other than substitution between these two species, adulteration with other species is not evident. Substitution of *P. polyphylla* also occurs due to the rising cost and scarcity of *P. polyphylla*, rhizomes, with rhizomes from several other *Paris* species being used and substitutes for *P. polyphylla*. And from a conservation perspective, the use of above-ground parts of *P. polyphylla* (Qin et al., 2018) would even be desirable, if this offers an acceptable form of substitution from a health perspective. With *O. sinensis*, adulteration can have negative health consequences. The high prices for *O. sinensis* (Fig. 4) occasionally result in a range of adulterants, including metal inserted into the bodies of the caterpillars to increase their weight and therefore payments to unscrupulous sellers. This may be the cause of lead-poisoning from

consuming *O. sinensis* (Wu et al., 1996). But this form of adulteration only works in the short term, affecting seller credibility and prices in the longer term. The need to detect adulteration where metal is inserted into the bodies of *O. sinensis* infected caterpillars has

also stimulated *O. sinensis* traders to either invest in large scanners for quality control (Fig. 9). As an additional back-up, some traders use hand-held metal detectors that they run over the caterpillar fungus bodies to detect metal inserts..

With Tokay geckos, the situation is more complex. Adulteration with other reptile species has been known for at least 20 years (Zhu and Ren, 1999) and DNA bar-coding techniques have been used to authenticate real *G. gecko* from fakes (Gu et al., 2011). In addition to use of a related gecko species (*Gekko japonicus* Schlegel and *G. swinhonis* Günther (Gekkonidae), some adulterants identified by Gu et al. (2011)

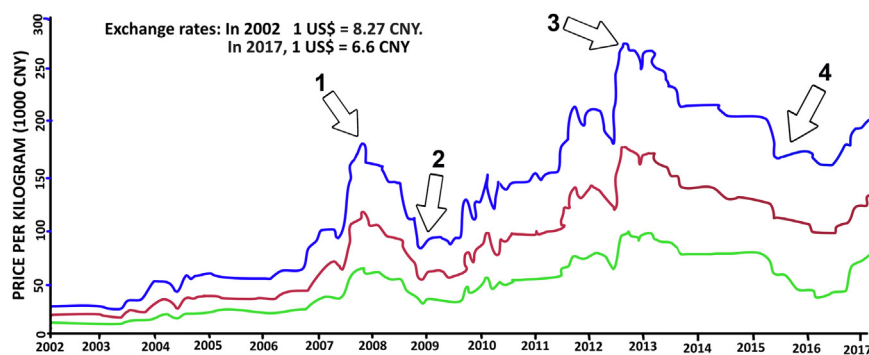


Fig. 4. *O. sinensis* prices 2002–2017 giving reasons for volatility: 1. Price increase for two reasons: (a) Businessmen expected that market demand for *O. sinensis* would increase, so speculating TCM buyers purchased lots of *O. sinensis* in that year and (b) export of *O. sinensis* increased substantially in that year. 2. Price decrease for two reasons (a) Capital flows in market reduced due to tighter monetary policy at the national level; and (b) export quantities declined due to the previously high price and due to the Global Financial Crisis (GFC). 3 (a) Production of *C. sinensis* was reduced due to an abnormal climatic event in that year and (b) the price of Chinese herbal medicine increased in general due to considerable capital flow from real estate and stock market profits into the Chinese herbal medicine market sector. 4. (a) Demand for

O. sinensis decreased due to government policies designed to combat corruption. This influenced the demand for *O. sinensis*, which is an expensive gift that amongst other things, is given as a gift to build business relationships (*guangxi*) and in some cases, bribery; (b) market supplies of *O. sinensis* increased due to increased wild harvests in that year, leading to price declines across all grades.

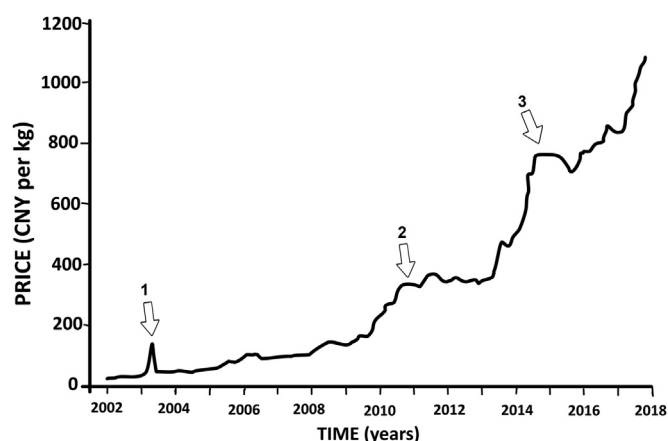


Fig. 5. *P. polyphylla* prices 2002–2017 giving reasons for more rapid price increases: Fundamental drivers of the steady price increase are rising demand and increased scarcity, with much less volatility than the three other species. 1. This spike in prices was probably due to the Severe Acute Respiratory Syndrome (SARS) outbreak (February–July 2003). 2. Price increased due to increased market price and high market demand. 3. Price increased due to low harvests and high commercial demand from traders.

were in separate reptile families: the Agamidae (*Calotes versicolor* Daudin, *Paralaudakia himalayana* Steindachner and *Phrynocephalus vlangalii* Strauch), Salamandridae (*Hypselotriton orientalis* David, *Paramesotriton chinensis* Gray and *Tylosotriton verrucosus* Anderson), Eublepharidae (*Goniurosaurus lichtenfelderi* Moquard) and Hynobiidae (*Batrachuperus pinchonii* David). We suggest that adulteration of *G. gecko* with these other species is driven by scarcity and opportunism. And for the narrowly distributed species *B. pinchonii*, which is endemic to western Sichuan and north-western Yunnan provinces in China, raises an issue of conservation concern, as *B. pinchonii* is already over-exploited for traditional Chinese medicine and for food, which have resulted in this species being ranked as Vulnerable on the IUCN Red List (Fei and Ye, 2004).

4.2. Factors that influence demand

4.2.1. Speculative buying behaviour drives volatility in some TCM markets

The influence of speculation on stock market price volatility is well known (Hardouvelis and Peristiani, 1992) and certainly applies to the TCM market as well. There is far less volatility in the *P. polyphylla* market, where stocks are well known to be scarce and where demand remains high and increases year by year. But for the other three species, volatility was high, and in common with *G. gecko* (Fig. 1) volatility in *O. sinensis* prices occurs for a variety of reasons across all grades (Fig. 4).

4.2.2. Market growth driven by rumours about therapeutic uses to treat epidemic disease

There are several examples of links between traditional medicine ingredient prices and outbreaks of potential epidemic diseases. *I. verum*, for example, is considered to be useful in treating the bird flu H5N1 viral strain (Wang et al., 2011). Increases in the price for Chinese star anise (*I. verum*) spiked during the 2009 Swine flu as well as during bird flu outbreaks, due to *I. verum* fruit use as a source of shikimic acid to produce Tamiflu (oseltamivir phosphate), which was being stockpiled at these times. Similarly, during the Severe Acute Respiratory Syndrome (SARS) outbreak (February–July 2003) demand (and prices) for increased *P. polyphylla* spiked (Fig. 5) due to the belief that *P. polyphylla* would be an ingredient in an effective treatment for SARS. Similarly, *G. gecko* sales increased due to rumours in Indonesia, Malaysia and the Philippines that *G. gecko* parts could cure human immunodeficiency virus (HIV) (Caillabet, 2011; Nijman et al., 2012b), a rumour one of us (A.B.-C) has also noted is also widespread in eastern Indonesia.

4.2.3. Sorting TCM products for quality

Quality influenced price/kg whether a TCM species had a relatively low price or a very high price. With Tokay geckos (*G. gecko*), there were three price levels, based on size and different prices/kg for small, medium and large geckos, Fig. 1). At the other extreme, are the five price levels for the very expensive caterpillar fungus (*O. sinensis*), ranging from broken product (where the fungal fruiting body is broken

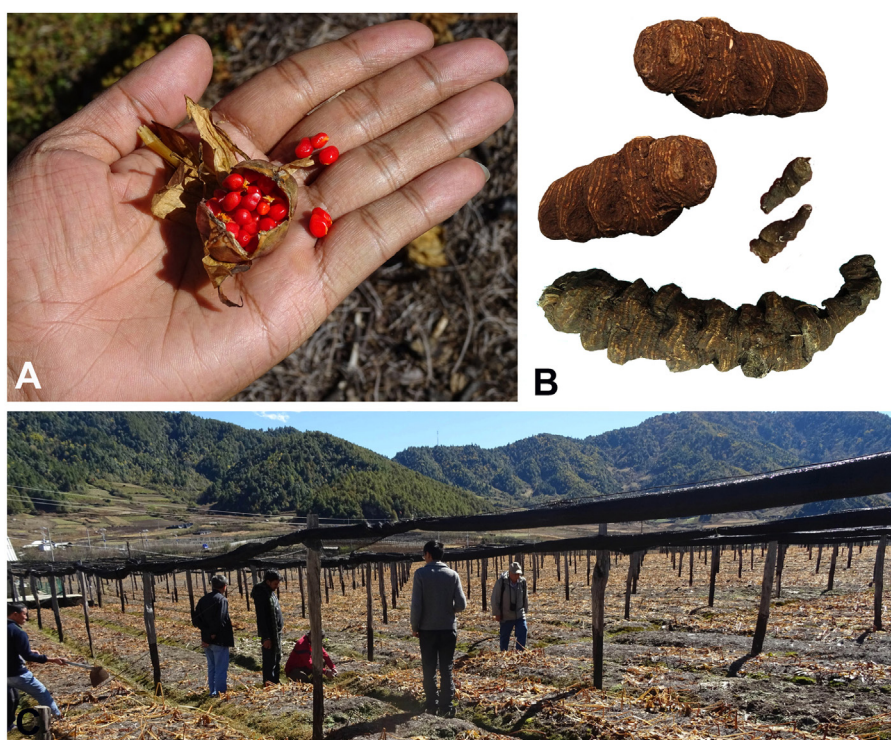
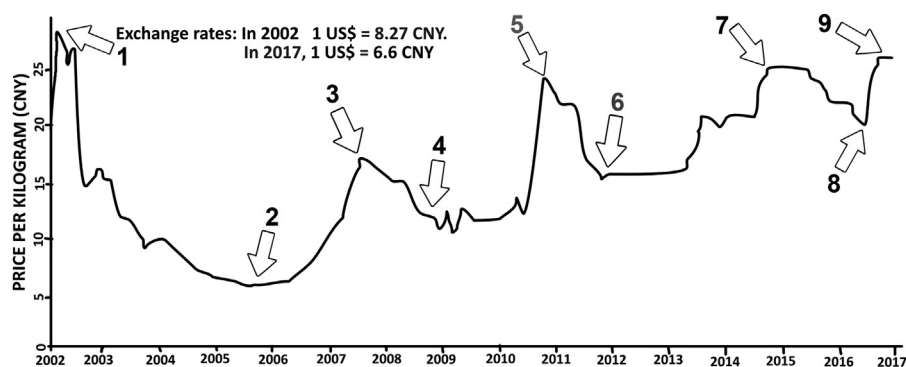


Fig. 6. Shifting from wild harvest to cultivation?. A. Cultivation by private enterprise, government and small-scale farmers has created a lucrative market for *P. polyphylla* seeds. B. Wild *P. polyphylla* rhizomes. C. Cultivation of *P. polyphylla* under shade cloth near Ludian, Yunnan, China at the end of the season when the annual above-ground parts are dry. photos: A. B. Cunningham.



due to increased market price and high market demand for the cultivated alternative species, *Schisandra chinensis*, *S. sphenanthera* and low demand from TCM traders. 7. Prices increased due to reduced production (because of drought) and increased commercial demand from traders. 8. Prices were in decline due to increased stocks and lower levels of buying by TCM traders. 9. Prices increased due to reduced production and more traders buying *S. sphenanthera*.



Fig. 8. A. Fresh, ripe *S. sphenanthera* fruits. B. Partly dried *S. sphenanthera* fruits. C. Grading *S. sphenanthera* fruits. photos: A. B. Cunningham.

from the dried caterpillar body) through to high value, intact, large caterpillar fungus (*O. sinensis*) (Fig. 3 and 4). Two of the four types of upgrading identified by Humphrey and Schmitz (2000) applied to the value-chains of the TCM species we studied. These were firstly, process upgrading, where new technology improves product quality (such as use of compressed air to clean *O. sinensis* (Fig. 3) or kiln drying of flattened Tokay geckos (Fig. 2). The second type of upgrading, product upgrading, is not indicated in wholesale price data, but certainly occurs further along the value-chain where TCM products are developed into diverse and more sophisticated product lines, with higher values per unit volume. Examples are luxury packaging for *O. sinensis* used as expensive gifts and preparation of extracts of *S. sphenanthera* in Shanghai before export to the USA.

4.2.4. Large-scale economic issues

Prices for *G. gecko* and *O. sinensis* were particularly affected by larger scale economic trends, such as a downturn in the overall TCM market in late 2015 and into 2016. And although the Chinese government quickly instituted strategies to reduce the impact of the Global Financial Crisis (GFC) that included a stimulus package for 2009 and

Fig. 7. *S. sphenanthera* prices 2002–2017 giving reasons for volatility. Since 2006, a fundamental driver of price increases for *S. sphenanthera* fruits has been the "ripple-effect" of price increases in the cultivated northern *Schisandra* (*S. chinensis*). 1. Prices increased due to a combination of lower production and lower stored stocks from the previous year's harvest. 2. Prices declined due to higher harvest levels and some TCM traders selling at a low price. 3. Prices increased due to cold climate and low fruiting success that reducing the production in mid-2007. 4. Prices declined due to the larger quantities that were harvested. In addition, as many TCM traders are risk-averse, the TCM traders took a "wait-and-see attitude", possibly also as a result of the Global Financial Crisis (GFC). 5. Prices increased



Fig. 9. Hehuachi market, Chengdu, China: as a quality control measure to detect slivers of metal inserted into the bodies of caterpillars infected with *O. sinensis*, some large wholesalers have invested in costly scanners that can scan large quantities of *O. sinensis* at a time.

2010 brought in in November 2008 (Li et al., 2012), price declines occurred for *S. sphenanthera* and *O. sinensis* between 2008 and 2010, when China's economy rebounded (Fig. 4 and 7). In contrast, *P. polyphylla* prices were much less volatile and continued to increase (Fig. 5), presumably due to the high demand for *P. polyphylla* rhizomes and well-known fact that wild stocks were in decline. Why *G. gecko* prices increased over this period (Fig. 1) is more difficult to explain.

4.2.5. Ripple effects from policy change

Prices of just one of the four focal species, *O. sinensis*, have been influenced by anti-corruption policy. While the background to this is straightforward, the reason why this influences caterpillar fungus prices requires careful consideration. Why did an anti-corruption campaign influence *O. sinensis* prices since early 2013 (see Fig. 4)? After all, policies to deal with corruption have been an issue of public concern in China well before 2013 (He, 2000). An important factor is that President Xi Jinping was elected in March 2013 and his anti-corruption campaign is considered "more sustained and severe than any previous one"

(Shambaugh, 2015). Understanding *guanxi* is central to answering the question about how *O. sinensis* prices. Social networks and gift exchange to build them are well known and well studied across many cultures (for example, Mauss's, 1954 classic anthropological study). *Guanxi* has a long history in China and refers to a process where good relationships are developed between individuals, creating "obligations for a continual exchange of favours" (Dunfee and Warren, 2001). There are different types of *guanxi*, with some types associated with bribery and corruption (Braendle et al., 2005). One of the gifts used to build *guanxi* are containing beautifully presented *O. sinensis* in sumptuously decorated boxes, often with red and yellow silk linings. Part of that anti-campaign since March 2013 has been to discourage influential individuals in accepting receiving expensive gifts or from attending luxurious banquets. And this, in turn, has influenced the decline in *O. sinensis* prices due to a decrease in their use as expensive gifts.

4.3. Factors that influence supply

4.3.1. Supply factors for wild populations: how much is out there?

With limited data on population numbers of any of the four focal species, Rabinowitz et al.'s (1986) approach, where geographic range, habitat specificity and expert opinion on relative population size are basic proxy measures of how much of a species is out there. And shown in Table 1, the focal species range from very widely distributed (*G. gecko*) to the narrow distribution and complex life history of *O. sinensis*. Tokay geckos (Fig. 1a), for example, are widespread through South Asia (Bangladesh, Bhutan, NE India, Nepal) and South-east Asia (Cambodia, Indonesia, Malaysia, Thailand) through to New Guinea (West Papua province, Indonesia). Tokay geckos have also adapted to living in people's homes and in cities. Although a very large bodied gecko species, their behaviour and reproductive biology have also enabled this species to also become invasive in Brazil and the southern USA (Florida) (Júnior, 2015). With this widespread distribution and adaptiveness, local over-exploitation is likely, but extinction is not. However, Gu et al. (2011) point out that due to habitat loss and hunting, *G. gecko* populations have declined significantly, with the resultant listing of *G. gecko* as a "Class 2 State Key Protected Animal" in China. Within its geographic range, *P. polyphylla* also occurs in a variety of habitats across a wide altitudinal range (from 100 to 3500 m asl). Despite a relatively wide geographic range and occurrence across diverse habitats, wild populations of *P. polyphylla* are in decline due to high impacts of selective harvest to collect the perennial rhizomes. And so does *S. sphenanthera* occurs in forests and thickets across a wide altitudinal range (700–200 m asl) in western and south-west China (in Anhui, Gansu, Guizhou, Henan, Hubei, Hunan, Jiangsu, Shaanxi, Shanxi, Sichuan, NE Yunnan and Zhejiang). *O. sinensis* on the other hand is restricted to the high altitude Himalaya (above 3000 m asl.)

4.3.2. Different harvester behaviour and varying impacts due to wild harvest

Resilience to harvest also influences whether wild harvest is sustainable or not. In the case of plants, fruit harvest (*S. sphenanthera*) has a lower impact than digging out rhizomes (*P. polyphylla*). With *G. gecko*, whole animals are harvested and with *O. sinensis*, the entomophagous fungi occur on their dead hosts (Hepialid moth larvae). Harvest impacts on *P. polyphylla* are discussed elsewhere in this special issue and wild populations are in decline (Cunningham et al., in press). *O. sinensis* populations also commonly considered to be declining due to over-exploitation (Negi et al., 2006) combined with habitat loss (Liang et al., 2008). Winkler (2008), on the other hand suggests that *O. sinensis* is only moderately vulnerable to overharvest. We agree with Winkler (2008) apart from one concern: climate change. Not only is resource management made more complex due to the complex life cycle of this entomophagous fungus and its high price (see Fig. 4), but may also due the effects of a warmer world on the high altitude habitat (3000–5000 m asl) of *O. sinensis*, as we discuss in the next section.

4.3.3. Climate: short term and long-term effects

Unlike long-lived herbal species such as *P. polyphylla*, which have underground rhizomes buffered from weather conditions (see Cunningham et al., in press, this volume), both *S. sphenanthera* and *O. sinensis* production is influenced by the weather. From field observation during a project on the *S. sphenanthera* trade in Sichuan, it is clear that unseasonal cold weather causes major declines in *S. sphenanthera* fruit production. Fluctuations in *O. sinensis* numbers may also be related to weather rather than to the effects of collecting. High yields probably relate to weather patterns in the preceding year, where relatively warm, high rainfall conditions caused by the monsoon and affects fungal spore dormancy on one hand, and the population dynamics of the Swift moth (Hepialid) caterpillars which *O. sinensis* spores infect on the other. High caterpillar numbers plus good weather for fungal spores result in high fungal caterpillar infection rates and consequent high yields to *O. sinensis* collectors, with consequent price decreases (Fig. 4, arrow 4 in 2015/2016). In the longer term, the picture may be bleak. Climate change is widely recognized across the Himalaya, exemplified by the Minyong glacier retreating over 200 m in just four years (Miura, 2007). Neither Stone (2008) nor other researchers working on *O. sinensis* harvesting have mentioned climate change, however. Interestingly, in a study of *Metarhizium flavoviride* W. Gams & Rozsypal, an entomophagous fungus in the same family as *O. sinensis* (the Clavicipitaceae), Hong et al. (1997), showed that spore viability and spore survival rates declined rapidly under moister, warmer conditions. The implications of that experimental study for climate change effects on wild *O. sinensis* are worrying. In addition, the complexity of *O. sinensis* dependence on the population dynamics of Hepialid moths and their food-plants shows how sustainable harvest becomes very complex and very challenging to manage at multiple spatial and time scales.

4.3.4. Does Homma's model apply?

This study suggests that the situation is more complex than the trajectory based on Homma's (1992) model, where higher prices would result in a shift to cultivation, thus replacing wild harvest. In the *O. sinensis* case, Homma (1992, 1996) was right: there has been a major investment in artificial production of *O. sinensis*, as Yue et al. (2013) describe in their review of cultivation methods for *O. sinensis*. These range from culture of fruiting bodies through to inoculation of moth (*Thitarodes armoricanus* Oberthür) larvae with mature fruiting bodies or cultured strains, then rearing infected larvae in underground areas planted with the larval food-plants. Products containing extracts from artificial cultivation are sold in China in capsule form. The relatively low price for products from artificial mycelial cultures is an indicator of consumer preference for the real thing: wild harvested *O. sinensis*. Yet farming of *O. sinensis* still needs to expand to a large scale, despite the amazingly high price for this product (Table 1). Successful cultivation does occur in China for many faster growing TCM species, including *L. barbarum* (goji) (Wei et al., 2006), *P. polyphylla* (Fig. 5 and Cunningham et al., 2018) and *S. chinensis* (bei wu wei zi). Li et al. (2015) reported that there are at least 29 areas in Yunnan where *P. polyphylla* is cultivated, with the highest production in Ludian, near Lijiang. Overall, there are between 3000 and 3500 ha of *P. polyphylla* under cultivation in China due high prices coupled to strong government and industry support. Yet prices for *P. polyphylla* rhizomes continue to increase, with no sign, as yet, of the decline in wild harvest predicted by Homma's (1992) model in response to cultivation. One reason for this is in Yunnan, most cultivated *P. polyphylla* is grown for the lucrative seed market and the rhizomes are not harvested. But in time Homma (1992) could be correct.

Trade in TCM raw materials is also influenced by rumours and lack of information amongst TCM traders that in turn may affect the profitability of captive breeding. The decline in the prices of *G. gecko* in 2005/2006 due to traders believing that Tokay geckos were now successfully domesticated (Fig. 1) is a good example. Which ironically would go against the Homma (1992, 1996) trajectory, if traders factor

in lower prices when cultivation really does occur, but needs to be profitable to expand. Captive breeding of Tokay geckos does occur in South-east Asia, but not on a scale that would support the export of millions of Tokay geckos to China (Nijman and Shepherd, 2015). And this misinformation is not restricted to *G. gecko* market traders, but also appears to be a misconception in some exporting countries. In 2014, for example, following a decision by the Indonesian Ministry of Forestry allow to Indonesian six companies to export over three million "live captive-bred" Tokay Geckos for the pet trade, Nijman and Shepherd (2015) carefully examined the logistics and financial needs of Tokay gecko domestication. They concluded that "the investments in terms of infrastructure, space, financial commitments and staff are not matched by the amount of money that can be made from the export of Tokay Geckos, especially if they are indeed intended for use in traditional medicines. In the authors' view it is impossible to maintain and breed these animals year-round and make a profit.... The inescapable conclusion is that if the quantities reported in trade are accurate, they can only be sustained through the routine laundering of wild-caught individuals and their export as dead specimens, rather than live for the pet trade. There is no legal trade in dead Tokay Geckos from Indonesia".

5. Conclusions

Price fluctuations in the four TCM species we examined are influenced by many factors and not just resource scarcity. And the situation is more complex than the trajectory based on Homma's (1992) model, where he predicted that higher prices would result in a shift to cultivation, thus replacing wild harvest. In case of both *O. sinensis* and *P. polyphylla*, Homma (1992, 1996) was right in terms of scarcity and high prices stimulating a major investment in cultivation (*P. polyphylla*) and artificial production (*O. sinensis*). But in both cases, intensive production through cultivation or artificial propagation do not yet occur on a large enough scale to reduce harvest of wild stocks. In the case of *G. gecko*, prices are too low for large-scale captive breeding to be viable. For *S. spheanthera*, a transition to cultivation is likely, if the history of *S. chinensis* is any guide. Substitution and adulteration occur with all four species. Improving information to medicinal plant traders on the supply status of TCM stocks, whether from wild harvest or from cultivation could benefit product quality, cultivation initiatives and conservation efforts.

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